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Review of electrical energy storage system for vehicular applications

Guizhou Ren*, Guoqing Ma, Ning Cong

School of Electromechanical and Automobile Engineering, Key Laboratory of Advanced Manufacturing and Control Technology in Universities of Shandong, Yantai University, 30 Qingquan Road Laishan District, Yantai 264005, PR China

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ABSTRACT

Recently, automotive original equipment manufacturers have focused their efforts on developing greener propulsion solutions in order to meet the societal demand and ecological need for clean transportation, so the development of new energy vehicle (NEV) has become a consensus among governments and automotive enterprises. Efficient electrical energy storage system (EESS) appears to be very promising for meeting the rapidly increased requirements of vehicular applications. It is necessary to understand performances of electrical energy storage technologies. Therefore, this paper reviews the various electrical energy storage technologies and their latest applications in vehicle, such as battery energy storage (BES), superconducting magnetic energy storage (SMES), flywheel energy storage (FES), ultra-capacitor (UC) energy storage (UCES) and hybrid energy storage (HES). The research priorities and difficulties of each electrical energy storage technology are also presented and compared. Afterwards, the key technologies of EESS design for vehicles are presented. In addition, several conventional EESSs for vehicle applications are also analyzed; the comparison on advantages and disadvantages of various conventional EESSs is highlighted. From the rigorous review, it is observed that almost all current conventional EESSs for vehicles cannot meet a high-efficiency of power flow over the full operation range; optimization of EESS and improved control strategies will become an important research topic. Finally, this paper especially focuses on a type of linear engine, a brand new automotive propulsion system used for NEV; the guiding principle of EESS design for the new type of linear engine is proposed, an overview of a novel hybrid EESS based on hybrid power source and series–parallel switchover of UC with high efficiency under wide power flow range for the type of linear engine is presented, and advanced features of the novel hybrid EESS are highlighted.

Contents

Abbreviations: AC, alternate current; BDPC, bi-directional DC–DC power converter; BES, battery energy storage; DC, direct current; EDLC, electric double-layer capacitor; EESS, electrical energy storage system; EMF, electromotive force; FCV, fuel cell vehicle; FC, fuel cell; FES, flywheel energy storage; FSMC, fuzzy sliding mode control; HES, hybrid energy storage; HEV, hybrid electric vehicle; ICE, internal combustion engine; kg, kilogram; kJ, kilojoule; kmh^{-1}, kilometer per hour; kW, kilowatt; kWh, kilowatt hour; LIB, lithium-ion battery; LIC, lithium-ion capacitor; Li-Ion, lithium-ion; NEV, new energy vehicle; PEV, pure electric vehicle; PSO, particle swarm optimization; PWM, pulse width modulation; rpm, revolutions per minute; SMC, sliding mode control; SMES, superconducting magnetic energy storage; SOC, state of charge; THS, Toyota hybrid system; UC, ultra-capacitor; UCES, ultra-capacitor energy storage; VSS, variable structure system

* Corresponding author. Tel.: +86 182 5353 1675; fax: +86 535 6902402.
E-mail address: renguizhou@tom.com (G. Ren).

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1. Introduction

In recent years, projections of energy use and greenhouse gas emissions for industrialized countries typically show continued growth in car ownership and vehicle use. The International Energy Agency (IEA, 2009b) projects an average annual increase in global transport energy demand of 1.6% between 2007 and 2030 [1]. In response, automobiles shift significant portions of their required energy from petroleum to other sources. Automotive original equipment manufacturers focus their efforts on developing greener propulsion solutions in order to meet the societal demand and ecological need for clean transportation. So the development of new energy vehicle (NEV) has become a consensus among governments and automotive enterprises.

NEV is defined as a vehicle which uses alternative fuel technologies and electrification technologies [2]. It refers to vehicle using unconventional vehicle fuel as a power source, or vehicle using conventional fuel with new automotive propulsion system, advanced integrated vehicle dynamics control and driving technologies.

The development and emergence of NEV can solve the problems such as the pressure and need to significantly reduce automotive gas emissions, the rising concerns about balance in the economy and energy security related to oil import and the excessive growth of the automotive industry. So the NEV industry with huge market potential has shown the development trend of competing.

NEV has gradually formed a “three vertical and three horizontal” technical route pattern (“three vertical” for hybrid electric vehicle (HEV), pure electric vehicle (PEV), fuel cell vehicle (FCV); “three horizontal” means multi-energy driving force for the total into the motor and its control system and power management system). As one of the key technologies of NEV, electrical energy storage technology through three vertical and three horizontal technology systems is seeking a new breakthrough and researched deeply.

Numerous private companies and national laboratories, many with federal support, are engaged in the related technology research for vehicle powerful electrical energy storage system (EESS) and development efforts across a very wide range of technologies and applications. In Ref. [3], a comprehensive overview of HEV with a focus on hybrid configurations, energy management strategies and electronic control units was studied, through discussion of several related technologies; they concluded that HEV was a hot subject today that had some advantages such as lower fuel consumption, lower operating costs, lower noise pollution, low emissions, smaller engine size and long operating life. HEVs and their challenges were reviewed in Ref. [4]; comprehensive survey of HEV on sources, models, energy management system developed by some researchers was provided in this study; they thought that HEV was the promising future transport option for the next generation, and this paper also presented many factors, challenges and problems sustainable to the next generation HEV. In Ref. [5], a regenerative braking system involves the installation of an additional motor/generator in parallel to the internal combustion engine (ICE) and was used in conjunction with a power converter and ultra-capacitor (UC); the experiments results showed that energy consumption was significantly reduced by adding regenerative braking to the vehicles. Omar et al. presented assessment of lithium-ion capacitor (LIC) for using in battery electric vehicle and HEV applications [6]; in this study the general characteristics of LIC were analyzed and compared with electric double-layer capacitor (EDLC) and lithium-ion battery (LIB). Various battery models for various simulation studies and applications were reviewed in Ref. [7], and advantages and disadvantages of each model were presented; this study has a great help for understanding the battery behavior and performance during charge and discharge. A review of battery–UC hybrid power source performance for pulsed current loads was presented and passive, semi-active and fully active hybrids were explained [8]; they concluded that hybridization of high energy battery and high power UC would solve the drawbacks of battery-only supply. A review of energy sources and energy management system in electric vehicles was presented by the researchers in [9]; they discussed the available energy source, energy generator for electric vehicle, power converter, low-level control energy management strategy and control algorithm use in HEV and PEV; they thought that the optimized efficiency and smart grid control strategy were the keys for the growth of electric vehicles.

However, most of the review studies published were focused on electrical energy storage technologies for conventional automotive propulsion systems and their applications; there is a lack of review studies which systematically focus on detailed design approach of EESS for new automotive propulsion system; this study is the first review study which investigates the EESS used in a new type of linear engine applications. The findings of this study contribute to literature for a broader understanding of EESS for NEV.

The aim of this paper is to review various electrical energy storage technologies and typical EESSs for vehicular applications that have been reported in recent years. Besides, EESS design methodology of linear engine for HEV is discussed. The paper is therefore organized as follows. After the introduction section, various electrical energy storage technologies and their main developing trends are described in Section 2. Key technologies of EESS design for vehicles are presented in Section 3. Several typical conventional EESSs for vehicle applications are discussed in Section 4. An overview of a novel hybrid EESS for a type of linear engine is presented in Section 5. Conclusions are summarized in Section 6 and the recommendations are given in Section 7.

2. Electrical energy storage technologies

The most common electrical energy storage technologies used in vehicles include battery energy storage (BES), superconducting

Table1
Comparisons of battery technologies.

Battery type	Lead–Acid	Ni–Cd	Ni–MH	Ni–Zn	Li-Ion
Energy density (W h/kg)	20–100	40–60	50–80	55–75	90–200
Power density (W/kg)	50–400	80–350	80–300	150–300	500–2000
Cycles	500–2000	600–3000	600–2000	600–1200	800–3000
Advantages	Low cost, mature technology, high specific power	High specific energy, no degradation for deep charge/discharge	High specific energy, large temperature ranges, safety, long service life	High specific energy, no degradation for deep charge/discharge, high peak power	High specific energy, high voltage operation
Disadvantages	Low specific energy, short service life	High cost cadmium toxicity, recycling issues	High cost, high self-discharge, memory effect	High cost, life shorten by fast growth of dendrites	High cost, life shorten by deep discharges, affected by temperature, fragile
Application stage	Widely used	Some used	Rarely used	Research and development	Research and development

magnetic energy storage (SMES), flywheel energy storage (FES), UC energy storage (UCES) and hybrid energy storage (HES) [10,11].

2.1. Battery energy storage technology

In the area of green transport, research on battery technologies is considered as the most important way in the next few years. BES has become the most widely used energy storage technology in NEVs. There are a few main types: Lead–Acid, Ni–Cd, Ni–Zn, Ni–MH, LIB (sometimes Li-Ion battery) and Na–S [10,12]. Over a long period of development, power batteries for NEVs have made a breakthrough [13,14].

A LIB is a member of the family of rechargeable battery types. With a reasonable energy density, less memory effect, and low self-discharging rate [15], lithium-ion batteries are becoming more and more popular for NEV applications [16]. For example, lithium-ion batteries are becoming a common replacement for the Lead–Acid batteries that have been used in a long time for golf carts and utility vehicles. Instead of heavy lead plates and acid electrolyte, the trend is to use a lightweight lithium/carbon anode and lithium iron phosphate cathode. Lithium-ion batteries can provide the same voltage as Lead–Acid batteries, so no modification to the vehicle's drive system is required [17].

In the US, lithium-ion batteries now power 100% electric vehicles such as the Nissan Leaf and Tesla Roadster as well as the hybrid Chevrolet Volt, which operates on electricity and gas [18–20]. The Ford Focus Electric, Honda Fit EV and Mitsubishi i-MiEV are electric vehicles all going to use the lithium-ion batteries [21,22]. While Toyota Motor has been endorsing more bulky, nickel–metal hydride batteries for the Prius model which sells in the U.S. market, it seems even Toyota is coming around to lithium-ion batteries [23]. Lithium-ion batteries are extremely promising to be used in the next generation NEVs [24,25].

Comparative advantages and disadvantages of various energy storage battery technologies and applications are summarized in Table 1 [10,26–29].

From above reviews, it can be seen that power battery will be the main choice of NEV market in a few years, with the development of battery technology and battery electric vehicle; infrastructures and charging stations for battery electric vehicle should be the future direction for governments and vehicle manufacturers, for example, a sufficient number of supercharging stations which can use wireless charging technology and can provide fast battery swapping within tens of seconds and fast charging within a few minutes.

And the comparisons of battery technologies shown in Table 1 indicate that each battery technology has different properties with regard to storage capacity, power, response time and cost. It is so hard to predict what kind of battery will be the leading product applied in the automotive engineering. State-of-the-art research and development of BES are generally focused on increasing their power, energy capacity, etc. Battery energy storage system cannot simultaneously meet the requirements of high power charge/discharge capacity, high efficiency, long cycle life [30], so some research institutions are carrying out exploratory studies which aim at improving the performance of the battery energy storage or seeking alternative products such as SMES, FES, UCES and HES.

2.2. Superconducting magnetic energy storage technology

SMES system is a device that stores energy in the magnetic field and can instantly release stored energy; it is considered as an ideal solution for shorter duration energy storage applications. The main characteristics of SMES are a strong power density, but a moderate energy density, a remarkably high (infinite) number of charge/discharge cycles and exceptionally high productivity in

power conversion, superior to 95%. SMES systems offer advantages in terms of quicker recharging and discharging, and the ability to recharge in a high frequency without degradation of magnets [31].

The main structure of an SMES system as shown in Fig. 1 consists of superconducting coil, AC–DC converter and DC–DC converter. The AC–DC converter rectifies alternate current (AC) to direct current (DC). After charging, the current does not decay, and energy can be stored almost without loss. The stored energy can be released back to capacitor *C* by discharging the superconducting coil through the DC–DC converter, then convert DC back to AC power through the AC–DC converter.

A quenching protection system is needed to dissipate the magnetic energy in case of a superconductor quench. A cooling system is also needed to keep the superconducting coil below the critical temperature.

In Ref. [29], SMES for regenerative braking may represent a possible alternative to electrochemical batteries or to developing technologies such as UCs or flywheels.

Based on studies of several review papers, it can be seen that SMES research and development have focused on developing high-temperature SMES devices. Due to the usage of low cost liquid nitrogen, the overall cost of system reduces. The high cost of SMES currently constraints the development of vehicle applications; however, significant reductions are needed to show an economic advantage over alternatives including batteries, capacitors, and power electronics alternatives [32–35].

2.3. Flywheel energy storage technology

FES works by accelerating a rotor (flywheel) to a tremendously high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy, adding energy to the system correspondingly results in a raise of the speed of the flywheel. A typical FES system as shown in Fig. 2 mainly includes three parts: flywheel rotor, motor/generator and power conversion subsystem. In electromechanical systems, the flywheel rotor is accelerated by motor/generator when operating in motor mode, the energy stored in the flywheel rotor is increased by accelerating the rotor to higher speeds, i.e. the FES is being charged. When required the energy stored in the flywheel rotor can be released by operating motor/generator in generator mode producing electricity. Conditioning of the electrical power to or from the motor/generator unit is achieved by power conversion subsystem.

FES applications in vehicles have crucial significance and become an international energy research focus [36–38]. In 2013 Volvo announced a flywheel system fitted to the rear axle of its S60 sedan. Braking action spins the flywheel at up to 60,000 rpm and stops the front-mounted engine. Flywheel energy is applied via a special transmission to partially or wholly power the vehicle. When partnered with a four-cylinder engine, it offers up to a 25% reduction in fuel consumption versus a comparably performing turbo six-cylinder, providing a 58.84 kW boost and allowing it to reach 100 kmh^{-1} in 5.5 s [39]. Flywheels may have been used in the experimental Chrysler Patriot [40].

Compared with other ways to store electricity, it can be seen that FES systems have long lifetimes, high energy density (100–130 W h/kg, or 360–500 kJ/kg) [41–44], and large maximum power output. The energy efficiency (ratio of energy out per energy in) of flywheels can be as high as 90%. Typical capacities range from 3 kWh to 133 kWh [41]. It should be noted that in practice, proposed flywheel systems should eliminate many of the disadvantages of battery power systems, such as low capacity, long charge times, heavy weight and short usable lifetimes. It is hoped that flywheel systems can replace conventional chemical batteries for electric vehicles.

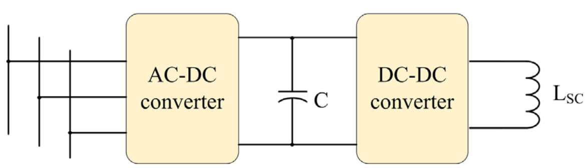

Fig. 1. SMES system scheme.

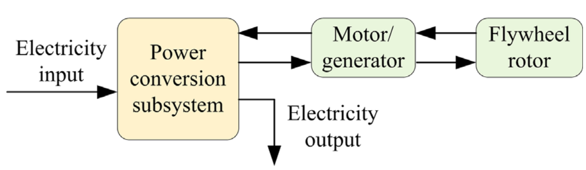

Fig. 2. FES system scheme.

2.4. UC energy storage technology

The response of UC during instantaneous and short-term peak power demand periods is relatively fast. Current from UC may be expected to go from charging mode to discharging mode rapidly, particularly for high repetition rate pulse applications. To meet the demanding conditions, UC can be used as a power buffer in a power electronic system or as an energy storage medium for pulse loads. UC as green, alternative energy resource is being used widely and considered in a host of future applications [45–55].

Table 2
Electrical parameters of UC of different manufacturers.

Manufacturers	Rated voltage (V)	Rated capacitance (F)	ESR DC (mΩ)	Time constant (s)	Energy density (W h/kg)	Power density (W/kg)	Weight (kg)	Volume (l)
Maxwell	2.7	3000	0.29	0.87	5.52	5400	0.55	0.475
Nesscap	2.7	5000	0.25	1.25	5.44	5063	0.93	0.713
Panasonic	2.5	2500	0.43	1.1	3.70	1035	0.395	0.328
EPCOS	2.7	3400	0.45	1.5	4.3	760	0.60	0.48
Asahi Glass	2.7	1375	2.5	3.4	4.9	390	0.21	0.151
Okamura Power sys.	2.7	1350	1.5	2.0	4.9	650	0.21	0.151
ESMA	1.7	80,000	0.5	40	13.38	583	2.4	1.68
JURONG	1.6	140,000	0.3	42	12.0	205	5.0	3.71
Spscap	2.7	9500	0.28	2.60	7.40	5010	1.3	0.97

Note: The time constant can be reflected by the internal resistance *R* and the capacitance *C* of UC. This time constant determines the time over which UC can be charged or discharged. For example, a 3000 F UC with an internal resistance of 0.29 mΩ has a time constant of $3000 \times 0.29 \times 10^{-3} = 0.87$ s. After 0.87 s charging with a current limited only by the internal resistance, the UC has 62.3% of full charge or is discharged to 36.8% of full charge.

UCs bridge the conventional capacitors and chemical batteries. Capacitance of UC is up to 10,000 times that of electrolytic capacitor, while existing UCs have energy densities that are approximately 10% of conventional batteries, their power density is 10–100 times greater [56]. UCs complement a primary power source like ICE, fuel cell (FC) or battery, which cannot repeatedly provide quick bursts of power. Some electrical parameters of UC of different manufacturers are shown in Table 2.

Recent developments in terms of time in the field of UC are LIC [57]. Compared to the EDLC, the LIC has a higher output voltage [58]. They have similar power densities, but energy density of an LIC is much higher. Since they combine high energy density with high power density, there is no need for additional electrical storage devices in various kinds of applications such as NEVs. Commercially available LIC offered the highest gravimetric energy density which can reach 15 W h/kg [59]. When the power density of UC reaches 80 W h/kg in EVs and HEVs, it can substitute the lithium-ion batteries, which cannot fit in point of energy density with the present UCs at the moment [60].

Most automotive manufacturers of NEVs have developed prototypes that use UCs instead of batteries to store braking energy in order to improve driveline efficiency. The Mazda 6 with a UCs recovering system called Intelligent Energy Loop (i-Eloop) reduces the fuel consumption to about 10% [45]. UCs can be used for brake energy recovering and supplying the energy for accelerating or starting [46].

We confirm that further improvement of UCs is going on. A great number of research and development departments are working to improve characteristics [47], such as increase in the energy density by developing new nanostructured electrodes, tailoring pore sized electrodes, and developing new pseudocapacitive coating or doping materials; increasing the power density by improving the electrolyte; increasing the cycle stability of pseudocapacitive electrodes and reducing the production cost.

2.5. Hybrid energy storage technology

Each energy storage technology has its own particular strengths and operational characteristics. Energy storage system with a single power source has significant limitations, and cannot meet the requirements of energy density and power density simultaneously.

UC can be combined with the battery to achieve the maximum efficiency for the power system [48–50]. The primary considerations are weight, volume and cost. There are many different types of hybrid power source which are formed by UC and battery [51–54]. UC can either be paralleled directly with battery or connected with battery through an active power converter like DC–DC. FC/battery hybrid power system can meet pulse power requirements with higher specific power and efficiency than the FC alone, still preserving high energy density. Refs. [51,52] that studied hybrid power source comprise FC and UC for EV applications. The FC is to supply mean power to the load, whereas the UC storage device is used as a power source to supply transient power demand. Test results have evidently revealed the excellent performances of the hybrid power source in conditions of overload and energy recovery in a short time.

Refs. [53,54] presented two structures of hybrid power source using UC as auxiliary storage plant, and FC as main power source. As shown in Fig. 3, the first hybrid source comprises a DC link supplied by FC and an irreversible DC–DC converter which maintains the DC voltage to its reference value, and UC is connected to the DC link through a reversible DC–DC converter allowing recovering or supplying energy through UC.

The second system, shown in Fig. 4, comprises of a DC link directly supplied by battery, FC connected to the DC link by a boost converter, and UC connected to the DC link through a reversible DC–DC converter. The role of FC and the battery is to supply mean power to the load, whereas UC is used to satisfy acceleration and regenerative braking requirements.

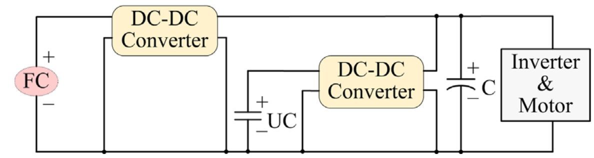

Fig. 3. Structure of the first hybrid system.

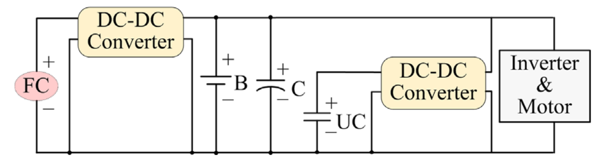

Fig. 4. Structure of the second hybrid system.

The above two systems are composed of FC, UC and with or without battery on DC link; these power sources use the FC as mean power source and UC as auxiliary transient power source. The simulation results show that many benefits can be expected from the proposed structures, such as supplying and absorbing the power peaks by using UC, recovering the energy by UC.

Results indicate that hybrid power systems can take advantage of each kind of device to yield a power source of both high power density and high energy density. It has consequently received much attention and been researched by automakers and governments, the energy storage techniques are quickly moving toward hybrid mode [53,54].

It can be seen that several technical challenges are associated with charging, storing and making use of power source to propel vehicles, and challenges of EESS for vehicles include providing vehicles levels of reliability and durability, package density, acceptable noise, vibration and harshness, and vehicle levels of cost in a set of new components and control strategy. So it is generally known that optimal design and proper control of EESS are the key issues to obtain a simple, compact and light-weight structure with high performance, high efficiency and good reliability. In the next section, key technologies of EESS design for vehicles are discussed comprehensively.

3. Key technologies of electrical energy storage system design for vehicles

The research field of EESS involves a lot of subjects, such as automotive electronics, power electronics, computer and control. The EESS should mainly consist of power source with both high specific energy and high specific power, power converter with low-cost, high-efficiency and easily control, and control strategy of power flow with high-efficiency and easily implemented [61]. So we can conclude that the key technologies of EESS for vehicles include the following three aspects: power source, power electronics and power flow control strategy.

3.1. Power source

The significant characteristics of power source are to achieve the objective of energy storage and bi-directional high efficiency power flow under the conditions of short time, high current and wide back EMF range, and to respond quickly and accurately.

Reasonable choices of power supply and parameters design are the keys of power source.

3.2. Power electronics

Power electronics are the electronics applied to conversion and control of electric power. The primary tasks of power electronics are to process and control the flow of electric power by supplying voltages and currents in a form that optimally suites for user loads. Power semiconductors and power electronics are the core products in contributing to the reduction of CO_2 emissions, as well as to improve power conservation for environmentally-friendly vehicle [62–64].

EESS is integration of power electronics, motion control and computer technologies, which covers a large number of power electronics technology applications, involving power devices, power conversion, motor drive, digital control and energy recovery technologies, etc. And problems related to the EESS waiting to be solved can be seen as follows: power converter topology design, power converter and power source parameter matching, power converter bi-directional high-speed switching, increasing the efficiency of power converter, four-quadrant power drive module design, electromagnetic compatibility and electromagnetic interference, signal sampling and so on. Power electronics technologies application in EESS is focused on power conversion and efficiency to improve overall system performance [65].

3.3. Power flow control strategy

Some advanced control algorithms such as fuzzy logic control and neural network control are gradually applied for power flow optimization in vehicles [66–68]. Fuzzy logic control strategy can obtain better results than traditional methods, but the fuzzy logic rules and membership functions mainly rely on experts' experience in order to get optimal results, which bring about some difficulties for the design of fuzzy controller [69]. The sliding mode control (SMC), which is derived from the variable structure system (VSS) theory, appears to be a powerful control technique that offers several advantages: stability even for large supply, load variations and robustness, superior dynamic response and simple implementation. Their capabilities emerge especially in application to power converters, yielding improved performance as compared to usual control techniques. Recently, fuzzy SMC (FSMC) has also been used for this purpose. FSMC provides the mechanism to design robust controllers for nonlinear systems with uncertainty. Applications of the FSMC to manage power flow of power source are increasing. Traditional fuzzy logic controller designed for energy management relies too much on the experts' experience, and is easy to get the sub-optimal performance. In order to overcome this drawback, in Ref. [70], particle swarm optimization (PSO) is introduced for energy management fuzzy controller design in dual-source propelled electric vehicles. PSO is adopted to optimize the fuzzy logic rules and membership in the fuzzy logic energy management controller. It can search the optimal solutions in the vector space automatically. The results show that the vehicle using PSO-fuzzy controller has a better fuel economy performance than that of using conventional fuzzy controller.

Power flow control strategy is an indispensable part in the design of EESS and the main factor that determines the efficiency [71]. In order to ensure a stable, reliable and efficient operation for the whole system, an optimal power flow control strategy is needed to make EESS possess high accuracy in the steady state and fast response capability in the transient state [72].

It is observed that the three categories for state of energy for EESS implementation are power source, power conversion and power flow control. In the next section, some typical EESSs developed by various researchers are discussed.

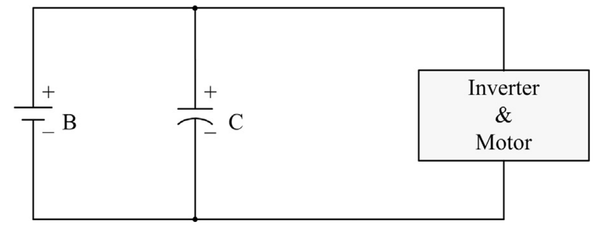

Fig. 5. The conversional motor drive system.

4. The conversional electrical energy storage system

Battery energy storage devices are used currently as a mainstream technology in NEVs applications. In vehicle applications, energy storage devices not only can provide energy for driving, but also can recover the braking energy. It is the conventional way for controlling the converter that converts the input voltage of power source into a lower output voltage of motor required [55,73–77].

The conversional vehicle motor drive system is shown in Fig. 5; when the system is working in the motor drive mode, the inverter operates in buck-mode by stepping-down the power source voltage through switching action and provides power to the propulsion vehicle. Conversely, in regenerative mode, the motor inductor is used as boost inductor of the inverter, and the inverter operates in boost-mode, stepping-up the back EMF generated by motor windings and recharging power source.

Regenerative braking refers to a process in which a portion of the kinetic energy of the vehicle is stored by EESS. Energy normally dissipated in the brakes is directed by a power transmission system to the energy store during deceleration. That energy is held until required again by the vehicle, whereby it is converted back into kinetic energy and used to accelerate the vehicle. The magnitude of the portion available for energy storage is proportional to the vehicle speed square. The back EMF generated by motor windings will decrease following the vehicle speed reduction until it cannot boost the power source voltage.

There have been so many literatures which focused on the conversional vehicle motor drive system, but, there is a lack of published papers which present the disadvantages of this type system. It is expected that this paper provides better understanding of disadvantages of the conversional vehicle motor drive system. The possible disadvantages of the above-mentioned energy storage devices can be summarized.

- The power source voltage must be greater than back EMF of the motor. The higher back EMF of the motor results in the higher power source voltage rating, which results in large volume and high cost of power source.
- A wide range of motor speed with a wide back EMF range; the variable ration of inverter is large, so the power conversion cannot be efficient.
- In braking energy regenerating system, the vehicle motor operates as a generator to charge the power source, but by limiting the variable ration of inverter, regeneration is not possible at low vehicle speeds. Because the back EMF cannot be boosted to the power source voltage through inverter, and thus the power source is not charged during low speed. For example, the city bus has the characteristics of low speed operation and frequent brake conditions, so regenerative brakes also lose their braking power and efficiency at low speeds.
- In regenerative braking, self-inductance of motor is performed as the boost inductor of inverter, the large inductor current ripple, results in the large heating generation, so the loss of the motor itself is increased. When self-inductance of motor is

small, a series of inductors is required to reduce the current ripple power loss, making the complex structure.

A typical electrical energy storage device used for NEVs is shown in Fig. 6 [78–81]; a hybrid power system in which UC and battery are connected through a bi-directional DC–DC converter is used in this application. UC is used to satisfy acceleration and regenerating braking requirements, accomplishing the transient system load requirement. The objective of the bi-directional DC–DC converter is to transfer power between the UC and the DC-link, keeping the DC-link voltage constant. This configuration shows that the device utilizes the characteristic of UC high power density. UC supplies or absorbs the peak current demanded by the load, so the battery peak current is significantly reduced, which extends the battery's cycle life. But the volume of converter inductor is large under large conversion current, the inductor efficiency losses increase rapidly. The nominal voltage of UC and battery difference cannot be too large because the voltage boost is not too high with high-efficiency through the DC–DC converter, which eliminates much flexibility in the system design.

In Refs. [82,83], an electrical energy storage device mainly used for HEV and EV over a wide speed adjustment range was presented, its topology is shown in Fig. 7 and the hybrid power system includes UC and battery. Three operating modes are obtained according to the UC voltage and motor speed. For urban driving at low speed braking and acceleration cycles, T1 is off, T2 is on or controlled by pulse width modulation (PWM), and UC is the only power source for the motor drive or regenerative braking. In wide acceleration range or high speed braking mode, T1 is on, T2 is off, and the inductor current can be controlled by adjusting the duty ratio of T3. UC as the main power source supplies the driving energy or absorbs regenerating energy, and the battery as the auxiliary power source provides additional power to the propulsion vehicle. In the mode III, the UC is charged by

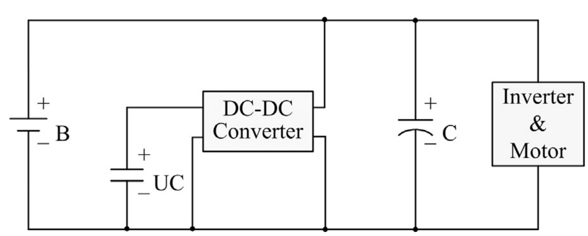

Fig. 6. A typical electrical energy storage device used for NEVs.

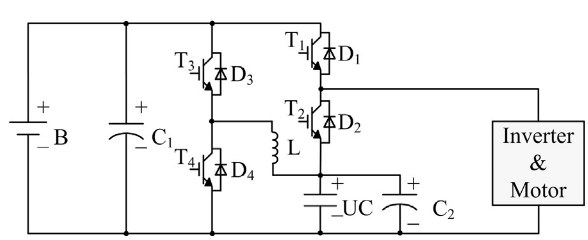

Fig. 7. The electrical energy storage device over a wide speed adjustment range.

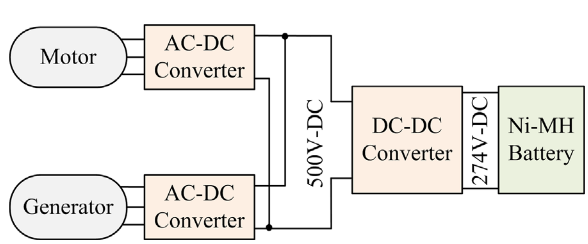

Fig. 8. The high-voltage power supply system of THS II.

battery when the small DC–DC converter is in the buck operation mode, T3 is controlled by PWM, T4 is off, and state of charge (SOC) of UC can be maintained at the set value.

We can observe that compared to the conversional electrical energy storage device such as shown in Fig. 5, the speed adjustment range of motor is extended and regenerating efficiency improvement is achieved by using a small rating buck converter. However, the method is achieved based on the situation that the motor speed is usually half rated speed to the full vehicle speed. The operating voltage of UC and battery difference cannot be too large. Only electrolytic capacitors are used to emulate the UC in laboratory validation, so effectiveness of the device needs to be further verified.

Based on Toyota hybrid system (THS), Toyota has developed a new-generation THS II which uses a high-voltage power supply system, the voltage of the motor and the generator are increased from 274 V-DC in THS to a maximum of 500 V-DC in THS II [84–86]. As a result, electrical power can be supplied to the motor with a smaller current, thus contributing to an increase in efficiency.

The high-voltage power supply system of THS II is shown in Fig. 8 [86]; we can recognize that compared to using the 500 V-DC high-voltage battery directly this reduces the volume and cost. By using the new connection structure between 274 V-DC low-voltage battery and a DC–DC converter that raises the supply voltage for the motor and generator to 500 V-DC, the efficiency is improved. Due to the small voltage variable ration between battery and DC-link, the speed adjustment range of motor is relatively narrow. When the battery is performing the single power source, it requires the high-performance battery in practical applications and it also cannot meet instantaneous power applications.

From the rigorous review, it is observed that almost all current conventional EESSs for vehicles cannot meet a high-efficiency of power flow over the full operation range; optimization of EESS and improved control strategies will become an important research topic. In the next section, an overview of design methodology for a novel hybrid EESS with high efficiency under wide power flow range for a new type of linear engine is presented.

5. A novel hybrid electrical energy storage system for a new type of linear engine used for vehicles

The novel automotive propulsion systems used for NEV such as linear engine or free-piston engine are under investigation by a number of research groups worldwide for their potential advantages, such as compact structure, power density, exceptional fuel adaptability and higher efficiency, making them extremely attractive as power systems of NEVs [87–89]. So a new research topic is proposed for the design of EESS from the composition to power flow control strategy.

5.1. Principle of a new type of linear engine

The schematic diagram of a new type of linear engine is shown in Fig. 9, mainly consisting of components of the combustion

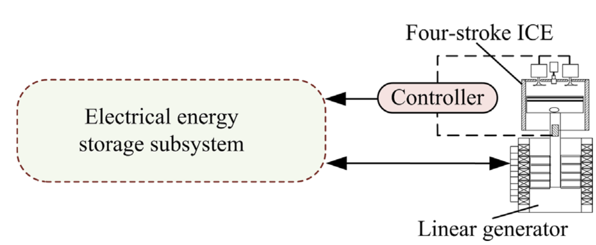

Fig. 9. Schematic diagram of a type of linear engine: (a) electromotor state and (b) generator state.

chamber for four-stroke ICE, linear generator, electrical energy storage subsystem and the controller [90,91].

Rotor of linear generator is connected with free-piston directly, which purely reciprocates movement together linearly when linear generator is working alternately as motor and generator periodically. The equivalent circuit of linear generator is shown in Fig. 10.

In the electromotor state, the voltage-balanced equation is given by

$$U_{AB} = \varepsilon + L_M \frac{di_M}{dt} + i_M r_M \quad (1)$$

where U_{AB} is the linear generator required terminal voltage, ε is the back electromotive force (EMF), L_M is the linear generator inductance, i_M is the linear generator current, and r_M is the linear generator resistance.

In the generator state, the voltage-balanced equation is given by

$$\varepsilon = L_M \frac{di_M}{dt} + i_M r_M + i_M R \quad (2)$$

where R is the equivalent load.

For linear generator, the electromagnetic force can be expressed as

$$F_e = K_i i_M \quad (3)$$

where F_e is the linear generator's electromagnetic force and K_i is the electromagnetic force constant.

And the back EMF is expressed by

$$\varepsilon = K_v v \quad (4)$$

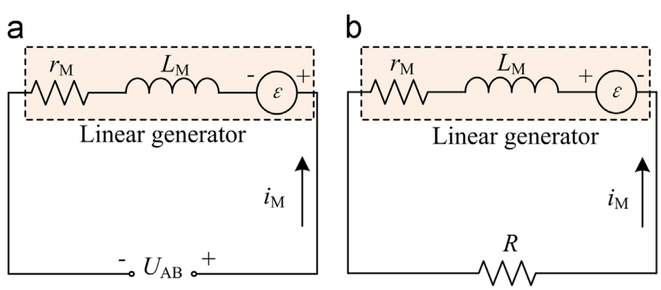

Fig. 10. The equivalent circuit of linear generator.

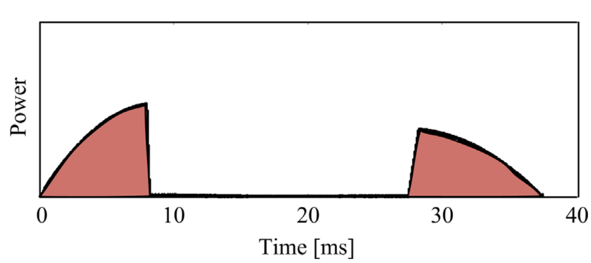

Fig. 11. The required energy when linear generator works in the motor state.

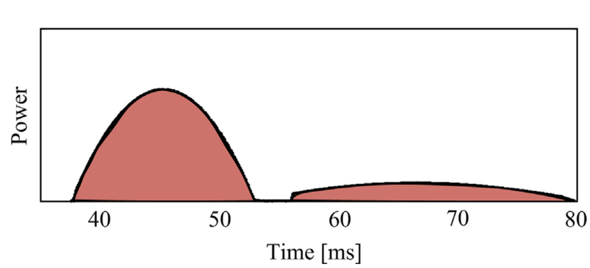

Fig. 12. The generated energy when linear generator works in the generation state.

where v is the piston assembly velocity and K_v is the back EMF constant.

When the linear generator is working in the electromotor mode, the electrical energy storage subsystem supplies power to control the movement frequency of the free-piston with the adjustable electromagnetic force; the steady output voltage of power source is inverted into the non-linear, wide range and continuous changeable terminal voltage which the linear generator requires. The required energy of linear generator is shown in Fig. 11. The power source absorbs power when linear generator is working in the generator mode; linear generator generates the non-linear, wide range, and continuous changeable back EMF which is inverted into a steady voltage of power source. The generated energy by linear generator is shown in Fig. 12, and the relationship of generated energy with linear generator' back EMF is shown in Fig. 13; the vertical axis is the back EMF, the abscissa is an energy percentage, and the curve represents the ratio of energy corresponding to back EMF to total energy.

In this motor system, electrical energy storage subsystem operates as the motor drive system to provide power for linear generator, or as the regenerative system to absorb energy generated by linear generator alternatively. Four quadrants working status of linear generator and the electrical energy storage subsystem are shown in Fig. 14, and the abscissa axis is the electromagnetic force; the vertical axis is the piston assembly velocity.

5.2. Requirements for electrical energy storage subsystem

To meet the regulation of the linear generator's electromagnetic force, adjustment and requirement of the piston assembly velocity, and to achieve the reasonable control of free-piston, the requirements for electrical energy storage subsystem are as follows: the higher power density and higher energy density; the instantaneous charge/discharge capability; the ability to control the four-quadrant operation of linear generator; the ability to achieve high-speed and accurate switching of linear generator between motor state and generator state, the switching frequency determined by the four-stroke cycle as well as the working time of each stoke; the ability to provide accurately armature winding current and terminal voltage for linear generator; and the ability to absorb energy efficiently generated by linear generator.

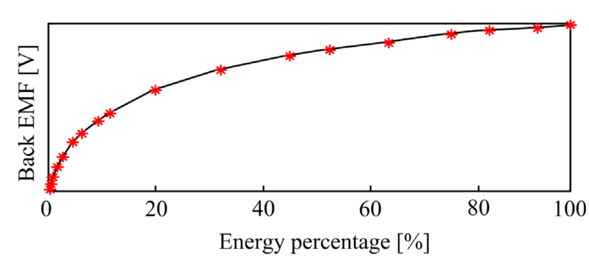

Fig. 13. The ratio of energy corresponding to back EMF to total energy.

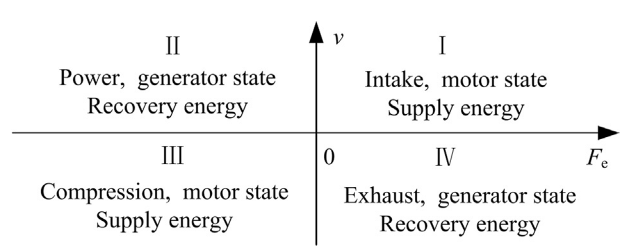

Fig. 14. Four quadrants working status of linear generator and electrical energy storage subsystem.

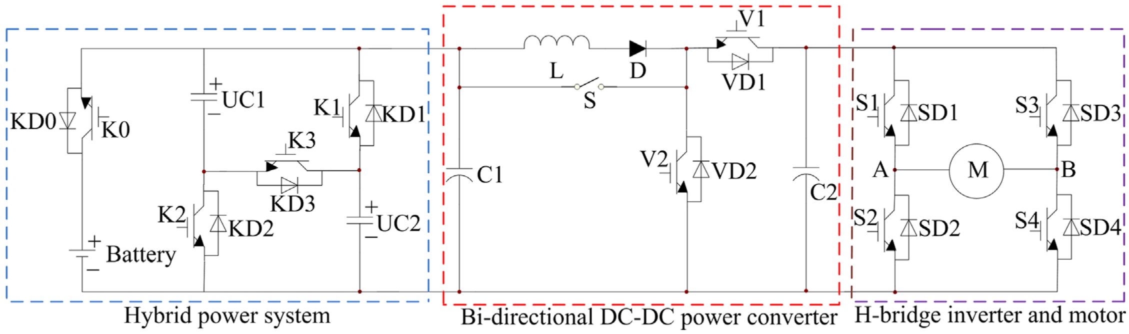

Fig. 15. Topology structure diagram of the novel hybrid electrical energy storage system.

The novel automotive propulsion systems used for NEV such as linear engine or free-piston engine have their own characteristics from working state to power flow process compared to conventional propulsion systems [92,93]; we recognize that EESS for linear engine should mainly be designed to be of high efficiency and practicability.

5.2.1. *High efficiency*

Linear engine can achieve clean and efficient power generation, from the electrical power flow point of view; the research of EESS has enormous significance to researchers in order to achieve the high efficiency of power transmission, conversion, control and storage.

5.2.2. *Practicability*

Linear engine has potential advantages such as compact structure, reasonable fuel adaptability and high efficiency over conventional engines. The system provides an advanced solution for HEV, distributed generation, and emergency power supply to replace the commonly used engine generator sets. It is considered to be a promising choice of automotive power plants for the future [87]. From the practicability point of view, the EESS should have smaller size to save space, lower price to save cost, and ideal control strategy to be easily implemented. The linear engine possesses the good traits shown above, which is considered to be an excellent solution.

5.3. *Proposed hybrid electrical energy storage system*

A hybrid EESS based on series–parallel switchover of UC banks for the new type of linear engine was proposed and researched by a research group belonging to [94–99], which was first used in NEVs, as shown in Fig. 15. The novel hybrid EESS includes a power source, bi-directional DC–DC power converter (BDPC), and H-bridge inverter. The power source is a hybrid power system, consisting of UC banks and battery banks. UC banks are controlled by series–parallel switchover as power buffer to achieve energy release and absorption; energy is required to be transformed into battery banks which are parallel with UC banks through switch with a certain control strategy committed by control unit. With the input energy, battery banks provide energy to other electrical equipments of vehicles.

Simulations and experiments reported in the references confirmed that, compared with the existing exploratory research, the proposed hybrid EESS has certain characteristics and advanced features, such as

- UC banks are connected in parallel with battery banks to form a UC/battery hybrid power source; UC banks are controlled by series–parallel switchover as power buffer to achieve power release and absorption. UC banks can be a power source supply when motor of the vehicle is in driving operation and absorb power in generating operation. With the input energy, battery banks mainly provide power to drive motor. So the advantages of high power density of UC banks and high energy density of battery banks are fully utilized, and effective control of power flow is achieved.
- The optimized BDPC reduces the volume and cost effectually, increases the efficiency, and is well positioned to meet the requirements of EESS. In Ref. [95], the characteristics of the proposed BDPC have been verified by experiments. The voltage conversion ratio of BDPC is always controlled within the ideal range under wide voltage range, due to the use of the series and parallel connection switchover technology for UC banks.
- Two regenerative braking modes are implemented [96,97]; the transferring efficiency and conversion efficiency of power flow between motor and power source of driving system are improved; thus the energy recovery within wide speed range is attained. Comparing with conventional breaking methods, the proposed method possesses the features of small size of driving system, low cost and high energy recovery efficiency.

From the previous studies of the proposed hybrid EESS, we recognize that the future work is the in-depth study on coordination among subsystems and integrated control strategy. The key scientific issues which need to be solved are optimization of the design parameters and control parameters; utility maximization for specific energy and specific power of hybrid power source; and optimization design of power flow control strategy which can be adjusted automatically according to vehicle operating conditions.

This approach significantly increases the motor speed adjustment range and the speed range of energy recovery compared to traditional design. Some results justify the effectiveness of design and control strategy. The novel hybrid EESS and the control strategy are also appropriate for motor drives with bi-directional power flow applications, such as power buffer system, power system and regenerative.

6. Conclusions

The awareness of environmental issue and energy crisis has brought up rapid development of NEV worldwide. Utilization of EESS will be a major step in the solution for the use of NEV along with the current issues of efficiency and practicability. So NEV studies are expected to be more popular in future years with development of electrical energy storage technologies. And there is a quite wide range of electrical energy storage technologies available for vehicular applications today or under development. The main conclusions of this paper are described as follows:

- This paper presents an overview of the main technical characteristics of various electrical energy storage technologies and their latest applications in vehicles. Advantages and disadvantages of each electrical energy storage technology are clearly emphasized. Results presented in this paper are based on a bibliographical review of the literature addressing electrical energy storage technologies. It is observed that the most widely used battery energy storage system cannot simultaneously meet the requirements of high power charge/discharge capacity, high efficiency, and long cycle life. The high cost of SMES currently constraints the development of vehicle applications. Proposed flywheel systems can eliminate many of the disadvantages of battery power systems, such as low capacity, long charge times, heavy weight and short usable lifetimes. It is hoped that flywheel systems can replace conventional chemical batteries for electric vehicles. UC as green, alternative energy resource is an emerging technology and being used widely and considered in a host of future applications, which really plays a key part in fulfilling the demands of EESS for vehicles. Hybridization of high energy battery and high power UC is shown as a possible solution, it has consequently received much attention and been researched by automakers and governments.
- The existing conversional EESSs for vehicles are classified and comprehensively described; it is observed that almost all current conventional EESSs for vehicles cannot meet a high-efficiency of power flow over the full operation range; the efficiency and performance of EESS should be further optimized to make NEV a viable option in transportation.
- An overview of design methodology for a novel hybrid EESS for linear engine in order to meet the requirements of high efficiency under wide power flow range is presented, and some results justify the effectiveness of design and control strategy. The hybrid EESS has great advantages compared to conventional methods which has important theoretical guidance and practical application value to the domestic research for improving the power conversion efficiency and transfer efficiency.

7. Recommendations

- Electrical energy storage technology is a multidisciplinary and strongly integrated technology. Large-capacity and high-density of EESS have a close relationship with materials science and chemistry science; if electricity of power source is generated from non-polluting, renewable sources, NEVs have the potential to produce zero emissions, so the researchers should be seeking a breakthrough in the related disciplines.
- In most electrical energy storage technology applications, energy conversions will be needed among various forms of energies; the rapid development of power electronics technologies has even realized high efficient EESS for vehicles, power electronics technology will be the key to make these conversions as efficiently as possible.
- Electrical energy storage devices not only meet the needs of practical applications, but also can maximize the capability, in order to give full play to the role of electrical energy storage devices; improved management strategies should be developed in order to effectively control the energy in time, space and strength.
- A variety of electrical energy storage technologies have different advantages and disadvantages, when designing electrical energy storage devices for vehicles; electrical energy storage technologies in scientific research, national defence construction, industrial and agricultural production applications can be learned.
- Optimization of hybrid power storage devices for NEV will become an important research direction.

Acknowledgments

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